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Application of a hybrid process for high precision manufacture of difficult to machine prismatic parts

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Abstract

In recent years, hybrid processes, which combine various individual manufacturing processes on a single platform, have drawn significant attention due to their ability to capitalise on the advantages of independent processes whilst minimising their disadvantages. Increased material removal rate, tool life, dimensional and geometric accuracy, and reduced production times have been achieved as some typical advantages of using hybrid processes. Despite the capabilities of individual processes continuously improving, production of highly accurate and complex structures, such as internal features, without assembly is still considered to be extremely difficult due to limited tool accessibility. This paper introduces a hybrid process entitled iAtractive, combining additive (i.e. Fused Filament Fabrication, FFF), subtractive (i.e. CNC machining) and inspection, which is capable of accurately producing complex part geometries. A novel process planning algorithm is developed, which addresses the three most important factors, namely, tool accessibility, production time and dimensional accuracy. A part is first orientated in a position and then decomposed into a number of subparts. The additive operations for producing these subparts together with the build directions are determined. The machining and inspection operations are then inserted into the scheduled additive operations, respectively, ensuring that the dimensions of the produced features are within the desired tolerances. A test part with internal features has been manufactured as one complete unit, where each surface of the features was finish machined, demonstrating the efficacy of the hybrid process and the process planning algorithm.

Key words:

Hybrid process, process planning, fused filament fabrication, CNC machining, inspection

1. Introduction

The ever-increasing customer demand for increasing varieties of products have led to the rapid developments and continuous evolvement in manufacturing technology over the past decades [1]. However, due to the technological constraints of individual manufacturing processes, it is not always feasible to produce components in terms of material, geometry, tolerance and strength etc. [2].

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Computer numerical controlled (CNC) machining provides the capability to generate components with extremely high levels of accuracy and surface finish, but it is still relatively difficult to machine certain complex geometries and shapes owing to tool inaccessibility problems [3], unless they are broken up into components and reassembled at a later stage. By contrast, Additive Manufacturing (AM) techniques, as one of the representatives of the new manufacturing techniques, are not constrained in the same way as CNC machining. The layer-by-layer fabrication approach indicates that the shapes of part cross sections can be arbitrarily complex, up to the resolution of the process [4]. Undercuts and internal features can be produced without specific process planning. Nevertheless, surface quality and accuracy impedes its further development for producing end user products with high accuracy [5]. Another typical process is injection moulding, which is not cost-effective in making customised products as individual moulds would be required [6]. The production cost increases exponentially when the quantity of parts to be produced significantly decreases. In addition, the need to separate mould pieces and eject parts greatly limits part complexity [4]. For forming process, the limited materials' formability and springback effect confines the process development [7]. The above examples indicate that the conventional individual manufacturing processes have their inherent drawbacks which cannot be completely eliminated.

As a result, hybrid techniques, which combine different processes together, have drawn significant attention due to their ability to capitalise on the advantages of independent processes whilst minimising their disadvantages. A 50% increase in material removal rate (MRR) was reported, while using the hybrid process combining mechanical drilling with laser, as compared to the individual mechanical drilling [8]. Recast layer and spatter can be dramatically reduced when using laser drilling and Electrochemical Machining (ECM) [9]. Increased tool life and reduced cutting forces in machining of hard materials (e.g. ceramics, Ti and Ni-based-alloys and Inconel[®] 718) have been achieved by employing ultrasonic assisted machining and thermally enhanced mechanical machining [10]. Despite the capabilities of individual processes continuing to improve the manufacture of precision complex structures (i.e. internal features), it is still considered to be extremely difficult to produce such structures without assembly, due to limited cutting tool accessibility.

This paper introduces a hybrid process entitled iAtractive, combining additive (i.e. FFF), subtractive (i.e. CNC machining) and inspection processes. A novel process planning algorithm has been specially developed for the manufacture of complex part geometries. In this study, if a prismatic part has the features (i.e. internal features) that are unable to be produced by using CNC machining techniques due to cutting tool inaccessibility, the geometry of the part is considered to be complex (i.e. difficult to machine). The major elements for realising the process planning algorithm are presented, including build direction determination, operation sequencing, feature modification and generation of dynamic process plans. Finally, a test part with two internal pockets and a blind hole, which are

virtually impossible to produce using a conventional manufacturing process, were manufactured as one complete unit, demonstrating the hybrid process and the presented process planning algorithm.

2. The state of the art in hybrid manufacturing technology

Various subtractive processes are utilised in hybrid subtractive processes. A high speed milling machine equipped with an Nd: YAG laser source has been developed by Quintana *et al* [11], which is capable of producing micro metallic components. Li *et al.* [12] reported a 100% increase in MRR compared to pure laser milling, while simultaneously applying a high speed abrasive jet to the laser melted pool for removing the molten metallic material in-situ. Kim *et al.* [13] applied laser cutting for rough machining of grooves and subsequently, micro-electrode discharge machining (micro-EDM) was employed to finish machine the parts, therefore significantly reducing the tool wear of the electrode.

In hybrid additive and subtractive processes, CNC machining processes are combined with additive processes, providing new solutions to the limitation of additive processes due to high accuracy, improved quality and speed that machining processes typically offer [14]. Jeng and Lin [15] used a laser to melt the mixed powders (Fe, Ni and Cr) and once one cladding operation was accomplished, the surface of the cladding was milled in order to achieve the desired accuracy and maintain a flat surface for the next cladding operation, until the entire mould was produced. Zhang and Liou [16] and Ren *et al.* [17] incorporated a laser cladding unit with a five-axis milling machine, where any deposition feature can be built in the horizontal direction by rotating the workstation. Thus, the need for supporting material during the deposition is eliminated, further reducing build times. Song and Park [18] utilised two gas metal arc welding (GMAW) guns for deposition of different materials, and CNC milling to fabricate injection mould inserts. Karunakaran *et al.* [5] retrofitted a 3-axis milling, which was used to face mill each slice built by metal inert gas and metal active gas welding. However, there is no robust process planning approach developed. The hybrid process just deposits one layer followed by a face milling operation. Further layers are deposited and machined until the entire part is produced. Therefore, Karunakaran *et al.* [19] argued that the need to face mill each layer is the major barrier for reducing production time. Xiong *et al.* [20] studied the mechanism of plasma arc deposition and integrated the plasma torch on a milling machine for manufacturing double helix impeller. The surface roughness of 2.32 μm was achieved but this hybrid process is not well utilised due to the lack of process planning techniques.

The integration of laser heating and machining processes has been identified as an effective method to improve surface quality and increase tool life [21]. Therefore, a large amount of research focuses on laser assisted machining processes. A focused laser beam is used as the heating source to irradiate the workpiece for improving the materials machinability. While the material is locally heated and

softened, it is removed by a conventional cutting tool [22]. Dumitrescu *et al.* [23] attempted to use a high power diode laser, suggesting that higher machining efficiency and better metal absorption can be expected. Anderson and Shin [24] proposed a new configuration in which two laser beams simultaneously irradiate a machined chamfer and an unmachined surface adjacent to the chamfer, respectively. In laser assisted water-jet cutting, trailing in the laser beam's path, a pure water-jet was used to produce localised thermal shock fractures.

Other combinations of manufacturing processes are also researched. Zhu *et al.* [25] investigated the mechanical-electrochemical machining of small holes by ECM and grinding, where a metal rod with abrasives was used as the cathode tool to mechanically and electrochemically machine the workpiece part. Dhokia *et al.* [6] developed a novel cryogenic CNC machining method, which sprays liquid nitrogen onto the workpiece (i.e. soft elastomer) to rapidly reduce the material to its glass transition temperature. This increases the stiffness of the low-density workpiece, allowing it to be machined by conventional CNC machining methods. In the paper by Araghi *et al.* [26], a stretch forming process was employed for pre-forming rough shapes. An asymmetric incremental sheet forming process was subsequently carried out to produce the final parts.

As compared to the rapid development of hybrid processes, very limited research has been reported on process planning of hybrid manufacturing. This is because there has not been a need for it since manufacturing has been limited to singular independent processes. Kerbrat *et al.* [27] used a design for manufacturing approach to analyse features in the design stage and subsequently identified which features would benefit from being made either by machining or additive process in terms of feature complexity. In the combination of additive and subtractive processes, a typical process planning approach is to face machine the top of each layer after it is deposited [15]. Hu and Lee [3] introduced a concave edge-based part decomposition method, which splits the part into a number of subparts to eliminate undercut edges during machining. Ruan *et al.* [28] and Liou *et al.* [29] developed a process planning approach that is able to decompose the parts, generate non-uniform layer thickness and tool paths for laser sintering and CNC machining by taking into account tool collisions.

3. A novel concept of hybrid manufacturing process

The concept of hybrid manufacturing (iAtractive) consists of combining additive, subtractive and inspection processes [30]. This is based on the need to reuse and remanufacture existing parts or even recycled and legacy parts; reduce the amount of material used; enhance the flexibility of CNC machining and improve the accuracy of FFF process. Incorporating an additive process releases design constraints often caused by tool accessibility issues in CNC machining. Using CNC machining capabilities the final part can be produced with a high degree of accuracy comparable to that of an entirely CNC machined part. Furthermore, dimensional information of the existing part can be

obtained by using an inspection technique (based on coordinate measuring machine) enabling the existing part to be further manufactured by an additive and/or subtractive process, providing new enhanced functionalities. This indicates that the iAtractive process is not constrained by part designs as well as raw material in terms of shape and geometry. The vision for the proposed hybrid process production is depicted in Fig. 1, where raw material can be (1) zero (filament for deposition from zero); or (2) an existing/legacy product; or (3) a billet. By using the additive, subtractive and inspection processes interchangeably, the given raw materials can be further produced to the finished part with complex geometries. It is noted that this paper focuses on scenarios where complex parts are manufactured from zero. ‘Zero’ in this case signifies that the iAtractive process starts with creating parts using filament as the raw material, as shown in Fig. 1(1).

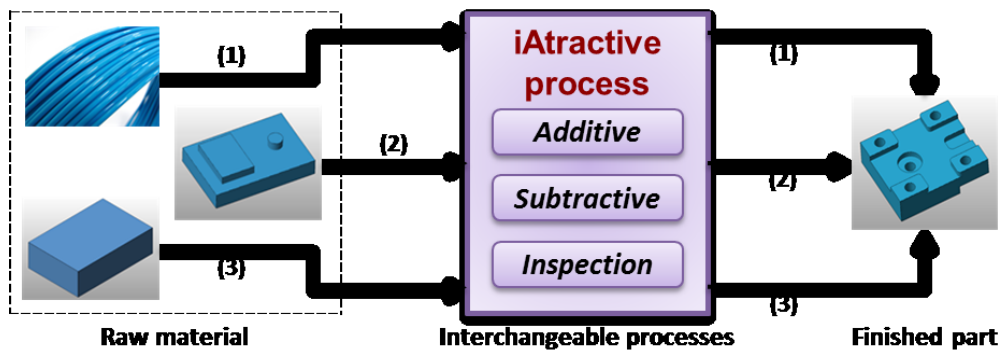


Fig. 1 Vision of the iAtractive process production.

4. Overview of the reactionary process planning algorithm for the iAtractive process

A reactionary process planning algorithm (RP²A) is developed and consists of two major stages, namely generation of static and dynamic process plans, which will be presented in sections 5 and 6, respectively. The overall goal of RP²A is to generate the process plan for a given design with complex part geometries.

The flexibility provided by the FFF process is utilised to create complex structures; CNC machining is used to finish machine the additively manufactured features, ensuring that the dimensions are within the designed tolerances. Four factors have to be taken into account, namely, cutting tool and deposition nozzle accessibility, production time, and dimensional accuracy. A static process plan is first generated, which is ready to use in the shop floor manufacturing environment. A dynamic process plan will be generated if any feature of the part is identified as being out of tolerances during production. The generation of a static process plan involves three major stages, namely, pre-processing, processing and post-processing. Among these three stages, the processing stage is the most important one as it identifies all viable operation sequences. Four major elements in the process stage have been developed, which are part decomposition, determination of build directions,

sequencing of additive and subtractive operations and feature modification. In the final sequenced operations, the additive, subtractive and inspection processes are used interchangeably to produce the complex part structures in the shortest time possible.

5. Generation of static process plans

5.1. The methodology for generation of static operation sequences

Unlike process planning for CNC machining where operation sequences largely determine production times and costs [31], the operation sequences for the manufacture of complex parts directly determines whether the parts (internal features in particular) can be accurately manufactured. Given that the iAtractive process utilises additive, subtractive and inspection processes, the traditional process planning methods [32,33] cannot be adopted since cutting tool accessibility for internal features are not considered in those methods. As a result, the authors have specifically developed a method for generating static operation sequences, as shown in Fig. 2, where the rectangular boxes represent the actions and the boxes with round corners are the outputs of the actions. The final output of this method is the most appropriate operation sequence in terms of production times.

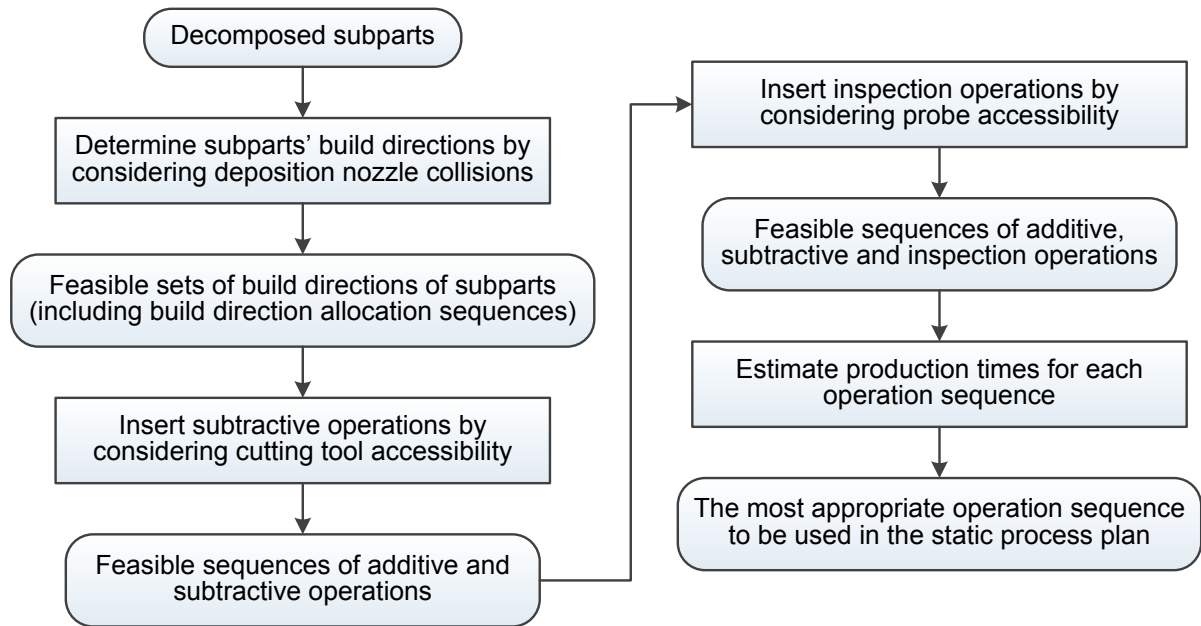


Fig. 2 The developed methodology for the generation of a static process plan.

In this method, the operations for additive, subtractive and inspection operations are considered independently in a certain sequence. Since a part will be produced from zero, it has to be built using the FFF process first. Due to the internal features that are required to be finish machined, the part has to be decomposed into a number of subparts, which will be introduced in section 5.3. Thus, the operation sequences for producing these subparts are determined by taking deposition nozzle

collisions into consideration (sections 5.4 and 5.5). Upon obtaining the sequences for building the subparts, the machining operations are inserted into the sequenced additive operations for machining the subparts where high surface quality and accuracy are required (section 5.6). The cutting tool accessibility is also considered, ensuring that it does not collide with the part during machining. Finally, the inspection operations are inserted into the generated additive and subtractive operations to ensure that the internal features are measured before they become inaccessible (section 5.8.1). By doing so, a number of feasible sets of operation sequences are scheduled. The most appropriate operation sequence is then identified using the production time and build time estimation models (section 5.8.2).

5.2. Pre-processing stage

The CAD model of the given part design is first pre-processed, extracting and interpreting features from the defined CAD model. The manufacturability of the part is analysed. Difficult to machine structures that would cause potential tool accessibility problem, such as internal and concave features, are identified. A part orientation is then specified. However, since the parts that this study deals with have internal features along multiple axes, there may not be an ideal orientation for a particular part. Orientating the part in this step is only a dummy activity since all the available orientations will be used and evaluated in order to obtain the most appropriate process sequence.

5.3. Part decomposition

The aim of decomposition is to enable complex parts to be manufactured as one complete unit rather than producing a number of pieces and assembling them together. The part is decomposed into a set of subparts based on primitives, which allows the internal features to be first produced to the required dimensions and tolerances. Subsequent features are then added. The decomposed subparts are named original subparts. The output of part decomposition is a set of original subparts, which will be further merged in the later stages. Part decomposition has to satisfy the following requirements:

- The features on the subparts should be exposed, which means these features are cutting tool accessible;
- The subparts can be clamped on a machine tool, which enables the features to be finish machined;
- No deposition nozzle collisions while depositing a subpart onto another subpart;
- The surface of the subpart on which another subpart will be built has to be flat since the FFF process is only able to deposit material on flat surfaces horizontally.

5.4. Determination of build directions

This section presents the method for determining build directions of decomposed subparts. The considerations and procedures in build direction determination are described.

5.4.1. Considerations in determination of build directions

In determining build directions, two issues should be addressed:

- (i) Deposition nozzle collisions may happen while depositing material in certain directions.

Owing to the working principle of the material deposition process, the FFF process can only produce parts layer by layer from the bottom to the top for a given part orientation. Fig. 3 shows the deposition nozzle on the FFF machine used in this study. Given the FFF deposition principles and the nozzle configuration as well as this study focusing on prismatic part manufacture, only six build directions are considered, which are $+x$, $-x$, $+y$, $-y$, $+z$ and $-z$. Unlike the laser based additive processes, the heated block and the nozzle are the major barriers in printing a subpart on a side face of another subpart.

A typical example is as follows: a part is comprised of three subparts. Fig. 4(a) shows the scenario where the deposition nozzle collides with subpart 2 while attempting to produce subpart 3 following the build direction indicated by the red arrow. As the build direction of subpart 3 in Fig. 4(a) is different from that of subpart 2, there is an interruption between printing subpart 2 and 3. This means subpart 2 has already been produced before starting to produce subpart 3. In this case, using the build direction for subpart 3 in Fig. 4(a) will undoubtedly lead to collisions. Alternatively, the build directions in Fig. 4(b) are feasible.

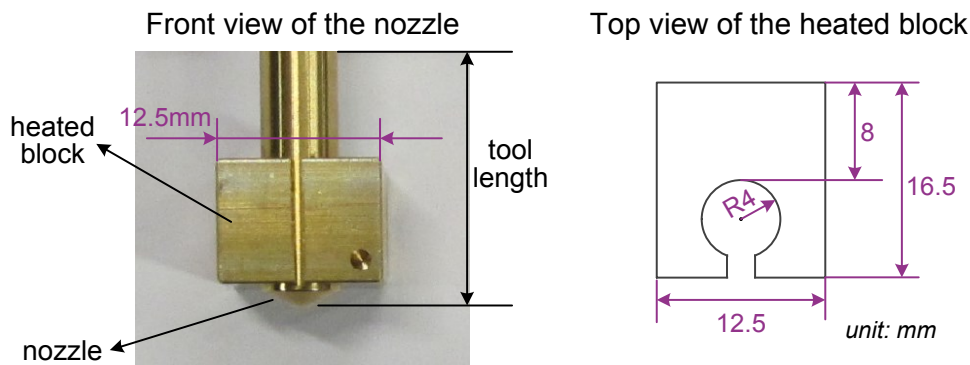


Fig. 3 The deposition nozzle of the FFF machine used in this study.

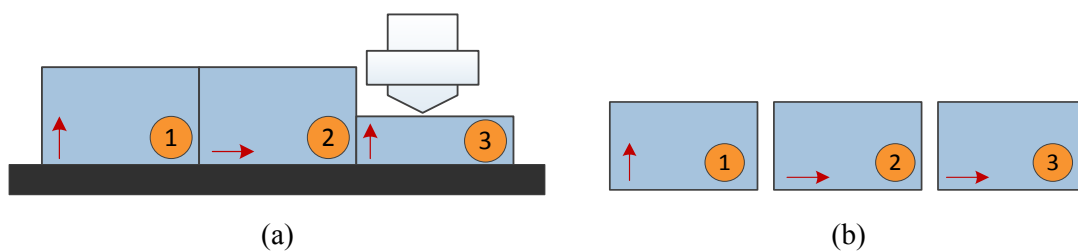


Fig. 4 Deposition nozzle collision.

- (ii) The specific operation sequences are restricted by the limitation of the FFF process, namely, features cannot be built without support.

There are two subparts, A and B. Having created subpart A using the build direction indicated in Fig. 5, the build direction of subpart B cannot be the same as that of subpart A, not only because of the deposition nozzle collision but also the lack of support beneath subpart B. As a result, subpart B has to be orientated to act as a build platform. Subpart B can then be deposited using the build direction as shown in Fig. 5.

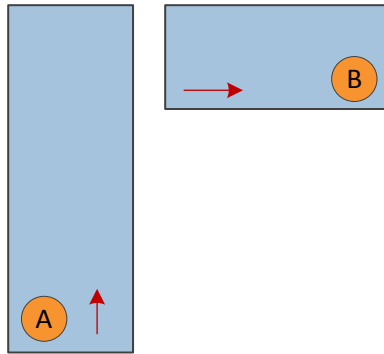


Fig. 5 Support is required when using certain build directions.

5.4.2. Procedures in determining subpart build directions

After decomposing the part into a number of original subparts, the build directions of these subparts will be determined. The major steps are outlined as follows:

- Based on the pre-determined part orientation and the given subparts, the build direction determination module starts allocating a build direction for the leftmost subpart located at the bottom of the entire part. The build direction of this subpart (called subpart 1 or the first subpart) should be exactly the same as the part orientation specified in the previous stage.
- The adjacent subpart is then selected and the available build directions are determined. If there is more than one subpart that is adjacent next to subpart 1, the subpart (called subpart 2) that shares the same base plane with subpart 1 is chosen first.
- The build directions of the rest of the subparts together with their adjacent subparts will be determined accordingly.
- The build directions of every subpart must be specified. However, the subparts of which the build directions have been allocated will not be subject to further build direction determination in one single run. If a part is decomposed into 4 subparts, each subpart is allocated a build direction and the build direction allocation sequence is subpart 1→2→3→4. This is considered as one single run. If there is another available allocation sequence, namely subpart 1→2→4→3. It is regarded

as another single run. When the build directions of all the subparts have been specified and no deposition nozzle collisions have occurred, this set of subparts' build directions is considered to be valid. Each single run can only have one or none valid set of build directions.

- Choose another subpart and set it as the first subpart to be determined a build direction until every subpart has been used as the first subpart once.
- Re-orient the entire part and implement the above steps until all the available part orientations (totally six orientations) have been performed.

The outcome of build direction determination based on a certain part orientation can be demonstrated in the graph shown in Fig. 6. Each branch represents a single run, which is also a set of build directions for producing the identical entire part. Each node represents an individual subpart with a certain build directions. Each black arrow represents the allocation sequence between two subparts. In each set of build directions, only one build direction is specified for each subpart. The build direction determination process moves forward (i.e. allocating build directions one by one). There are x subparts that are adjacent to subpart 2 (i.e. subpart 3, 4 and etc.). As a result, there are x branches expanding from subpart 2. The subparts in each dashed block are identical but have different available build directions. Subpart 4 has a number of build directions and thus, there are a number of corresponding branches spreading from subpart 3. Subpart n has two neighbouring subparts and consequently, there are two branches expanding from it.

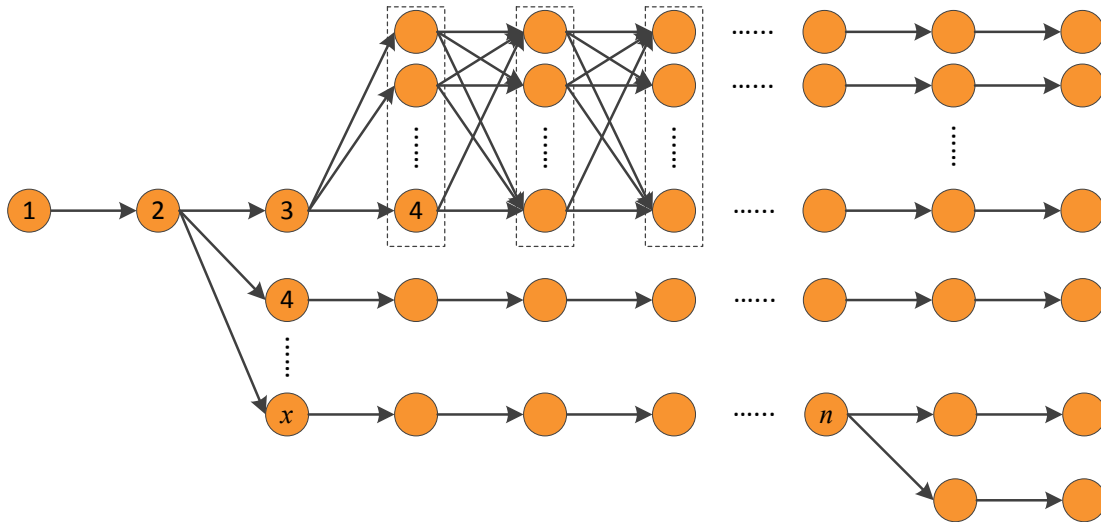


Fig. 6 The results obtained in build direction determination.

5.4.3. Relationships between two successive subparts in a set of build directions

As introduced in section 5.3, the subparts obtained from part decomposition are termed original subparts. If two original subparts in a set of build directions are allocated build directions in sequence, they are considered to be successive subparts. The relationships between two successive subparts in a set of build directions are categorised as parent, child, twin and unconnected. The parent and child

relationship is generated as a result of additive operation interruption, as explained in section 5.4.1(i) and Fig. 4. A subpart that has to be deposited onto another subpart is considered to be a child part. The twin relationship indicates these two subparts may be produced simultaneously by sharing the same build platform. Unconnected subparts are the subparts that are not physically connected to each other. However, it should be pointed out that the relationship between two successive subparts is only valid in a certain set of build directions in a certain part orientation. In different sets of build directions, the relationship between the two successive subparts may vary.

5.5. Subpart merging

Subpart merging is only applied to the FFF process and the aim is to provide more viable build directions and reduces the risks of deposition tool collisions through combining two or more original subparts together. The two original subparts can be merged into one subpart if they meet the requirements below:

- They are adjacent subparts
- They are successive subparts in a set of build directions
- They have the same build direction

A merged subpart can further be merged with its adjacent original subparts if they have the same build direction. The sequence of subpart merging should follow the sequence in allocating build directions for original subparts. It is noted that the results of subpart merging may be different from one set to another set of build directions. Subpart 2 and 3 in Fig. 4(b) can be merged into one subpart.

Subpart merging is preferable when two adjacent subparts can either be produced in series or simultaneously. This is because producing merged subparts can lead to reduction in production time. Subpart merging also provides more available build directions for original subparts. For instance, in Fig. 4(b), if subpart 1 has been produced before starting to create subpart 2, this leaves only one available build direction (i.e. \rightarrow) for subpart 2. In addition, if subpart 1 is built separately with the build direction indicated in Fig. 4(b), it has to be machined and measured before depositing subpart 2. If subpart 1 and 2 are merged and built together, the time used in machining and measuring subpart 1 can be eliminated.

5.6. Sequencing of additive and subtractive operations

This section presents the method and constraints that are applied in sequencing of additive and subtractive operations.

5.6.1. The method for sequencing of additive and subtractive operations

Fig. 7 illustrates the work flow of build direction determination, operation selection and sequencing in RP²A. A given part is decomposed into a number of subparts. The viable build directions for each subpart are then identified followed by subpart merging. Subsequently the sequence of the additive and subtractive operations is scheduled, which takes cutting tool accessibility into consideration. In certain scenarios the feasible sequence for producing the part cannot be found due to the limitations of the FFF and CNC machining processes. In this case, the merged subparts that lead to the failure in operation sequencing will be re-decomposed into the original subparts. Having obtained one feasible sequence, other possible sequences will also be identified if the subparts have other viable build directions. This entire process is then applied to other part orientations, identifying other sequences that can potentially be used to manufacture the part.

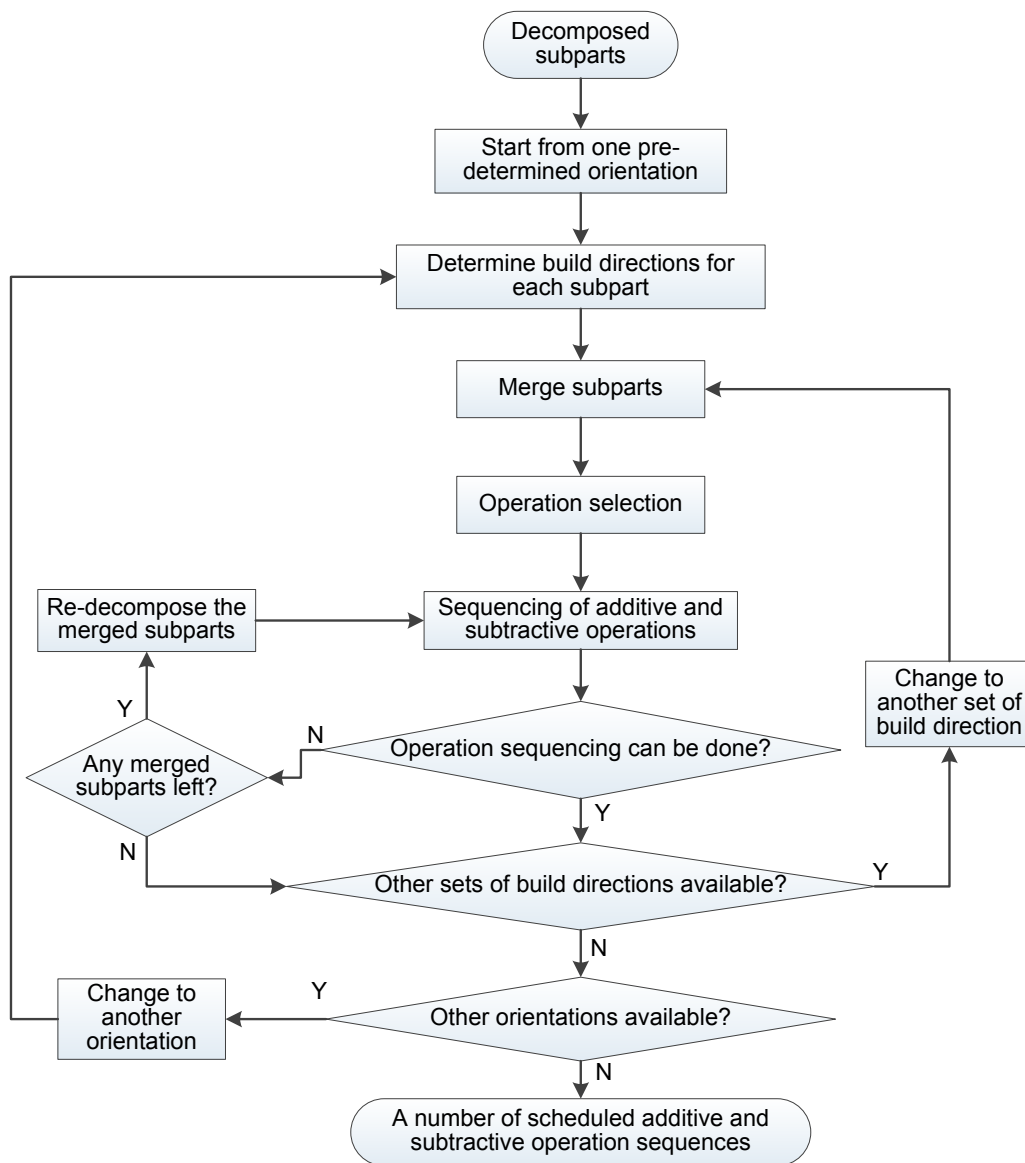


Fig. 7 The work flow of build direction determination, operation selection and sequencing.

5.6.2. Operation selection

Operation selection is a broad topic in process planning research, which involves a large number of factors to take into consideration, such as part geometry and cost [34]. In this study, operation selection is restricted in a very narrow area. Operations used in the iAtractive process are classified into additive operations in the form of FFF, subtractive operations in the form of CNC machining, inspection, switch operations.

5.6.3. Precedence constraints

- *Dimensional accuracy constraints.* For the features where low surface roughness and high accuracy are specified in the part design, a machining operation must be used to ensure the surface quality and dimensional accuracy.
- *Build direction allocation sequence constraints.* This type of constraint means the operations for making the child feature have to be scheduled after the operations that are used to produce the parent part. Moreover, the operations to produce two unconnected subparts should follow the allocation sequence of build directions.
- *Machining constraints.* A feasible operation sequence should also comply with the machining constraints that come from geometrical and technological considerations. The detail of the machining precedence constraints between machining operations can be referred to Li *et al.*'s [35] work.

5.6.4. Tool accessibility constraints

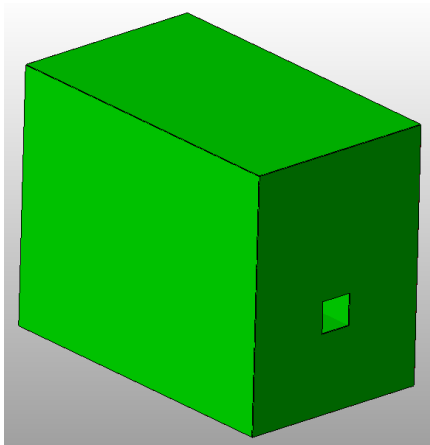
Tool accessibility is one of the most important factors to be considered in RP²A as this directly determines whether or not a feature, especially an internal feature, can be built and machined. Tool accessibility constraints consist of cutting tool accessibility and deposition nozzle accessibility. The deposition nozzle accessibility has already been illustrated in section 5.4.1. Cutting tool accessibility is concerned with tool approach direction (TAD). In a 3-axis machining environment, there are six TADs, i.e. +x, -x, +y, -y, +z and -z. This study only focuses on whether a cutting tool or deposition nozzle can have the access to features. As long as the feature is accessible, it is considered as machinable and/or buildable.

5.6.5. Considerations in operation sequencing

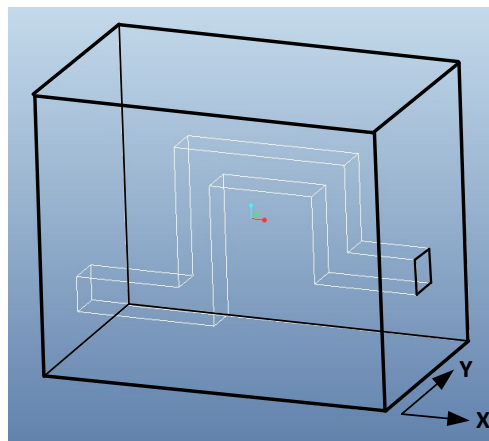
- (i) A subtractive operation should be scheduled to finish machine the bottom surface of the part/subpart/feature due to part distortions.
- (ii) Multiple and repetitive machining operations for the same feature should be avoided.
- (iii) Certain machined features/surfaces on a subpart will become un-machined again if there is more material to be added onto the subpart.

An example can be found in Fig. 8, where each surface of the part is required to be machined to achieve the correct surface quality and tolerances. Fig. 8(b) is the internal view of the part, which has five connected pockets. For better representation, round corners are intentionally ignored in Fig. 8(b). The decomposed result is also shown in Fig. 8(c). Twenty three subparts are merged into 5 as some of them have the same build directions. The merged subparts together with their build directions are shown in Fig. 8(d). It should be noted that the result of subpart merging shown in Fig. 8(d) is only valid for this set of build directions. The overall sequence is to manufacture subparts from 1 to 5 by interchangeable FFF and CNC machining processes. Even though subpart 1 has been finish machined, the surface highlighted by the black arrow become rough (un-machined) again once subpart 2 is added, as shown in Fig. 8(d). In addition, finishing operations are also needed for the two highlighted pocketed on subpart 2 once subpart 3 and 4 are added, respectively.

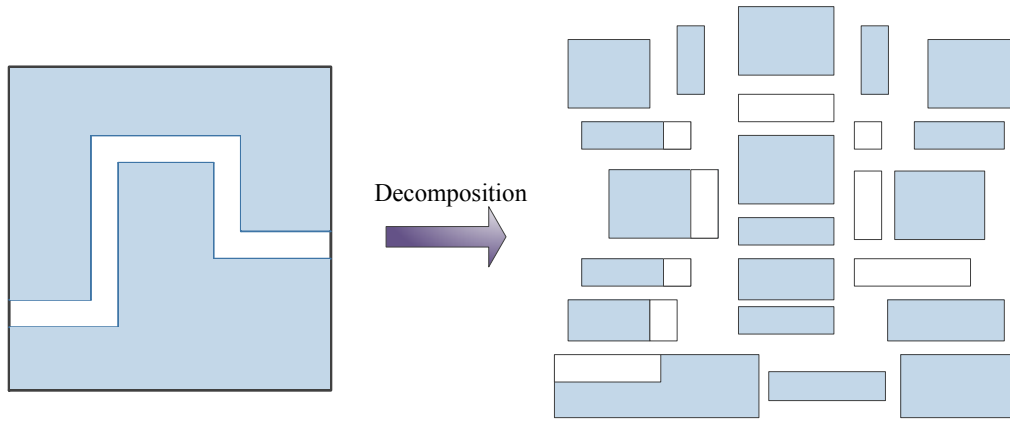
It is noted that, since these highlighted surfaces are subject to repetitive machining operations, there is no need to machine them until new subparts are added resulting in cutting tool inaccessibility. In other words, subpart 1 does not have to be finish machined prior to adding subpart 2. Having added subpart 2, subpart 1 can then be machined since the pockets on subpart 1 are still accessible. As a result, the total number of repetitive machining operations is reduced. It is also noted that the majority of failures in operation sequencing are attributed to the machined features that become un-machined when more subparts are stacked up. Fig. 8(e) shows the merged subparts obtained from another set of build directions based on a certain part orientation. The operation sequence is to manufacture subpart 1, 2 and 3. However, the surface highlighted by the black arrow in Fig. 8(e) becomes rough again once subpart 3 is built. In this case, the surface cannot be further machined as the cutting tool can no longer access the pocket on subpart 1.



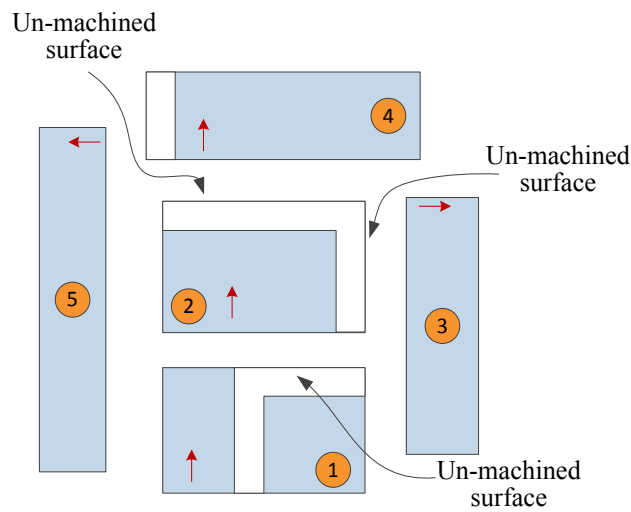
(a) example part



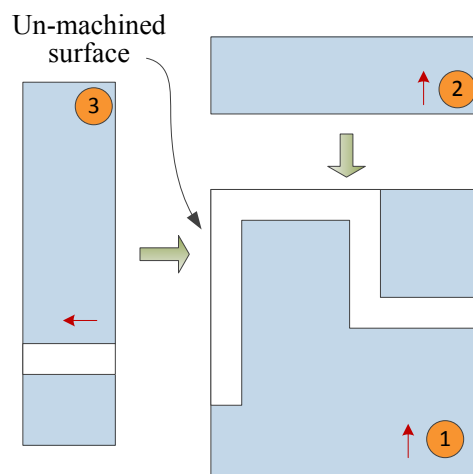
(b) internal view



(c) cross-sectional view and part decomposition results



(d) build directions and merged subparts



(e) failure in operation sequencing

Fig. 8 Repetitive machining operation and un-machined surfaces.

5.6.6. Re-decomposition of merged subparts

Due to cutting tool and deposition nozzle accessibility that has been considered in part decomposition, the original subparts are free to be produced without any tool accessibility constraints. However, more

constraints are induced as a result of a number of original subparts that have been merged, which leads to further tool accessibility issues. In this case, the merged subparts that lead to the failure in operation sequencing will be re-decomposed into the original subparts, releasing the constraints. The build directions of these re-decomposed subparts should be the same as the directions that are specified in the build direction determination stage. These re-decomposed subparts will not be combined in the subsequent stages again because combining them is likely to bring the constraints back leading to the operation sequencing failure. Fig. 9 shows the sectional view of a part that has internal pockets. If subpart 1 and 2 were merged as they had the same build directions (denoted by the red arrows), the blind pocket would not have been machined. Therefore, the combination of subpart 1 and 2 has to be separated.

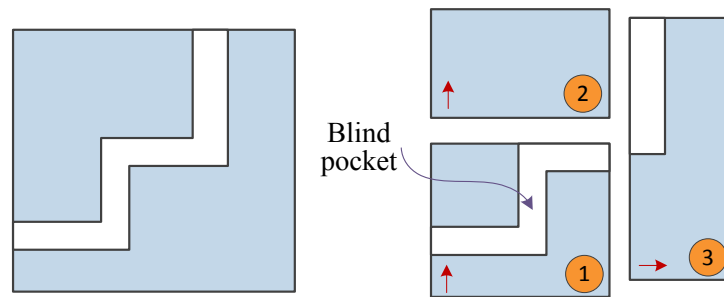


Fig. 9 Re-decomposing merged subparts.

5.6.7. Procedures in sequencing additive and subtractive operations

After determining build directions for each subpart and obtaining merged subparts, the sequence of addition and subtractive operations will be scheduled for each valid set of build directions. For a given part orientation, a certain number of feasible sequences may exist due to some subparts that have multiple build directions and adjacent subparts. Other possible sequences that result from different orientations will also be identified. The procedures for sequencing additive and subtractive operations for a single set of build directions are illustrated in Fig. 10. As presented in section 5.6.6, a viable sequence might not be found for a certain set of build directions when the part is positioned in certain orientations (an error occurs in Fig. 10).

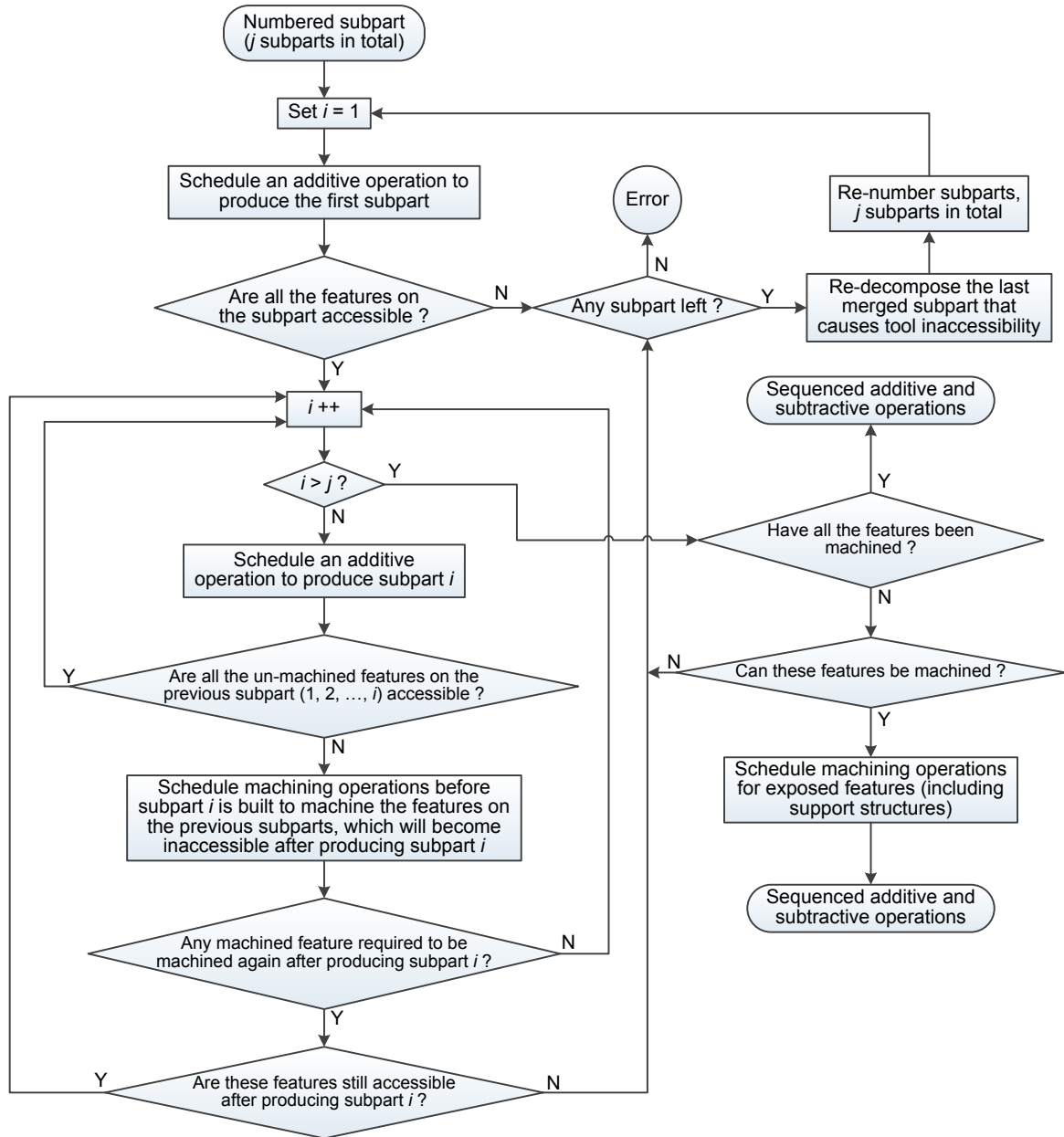


Fig. 10 The procedures for sequencing additive and subtractive operations.

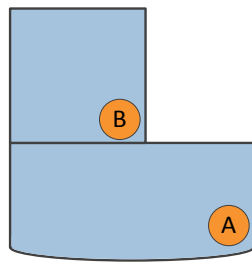
The major steps are outlined as follows:

- The first subpart (i.e. subpart 1) will be built followed by adding more subparts until the features on the subparts cannot be machined due to cutting tool inaccessibility.
- After scheduling a subtractive operation for machining a feature on a subpart, it is necessary to identify whether or not the feature (or any surface on the feature) will become rough again once the subsequent subpart is added onto the machined subparts. If this is the case, it has to be identified whether or not the feature is still accessible when the subsequent subpart is added. If the cutting tool still has access to the feature, the subsequent subpart can be built onto the machined subparts.

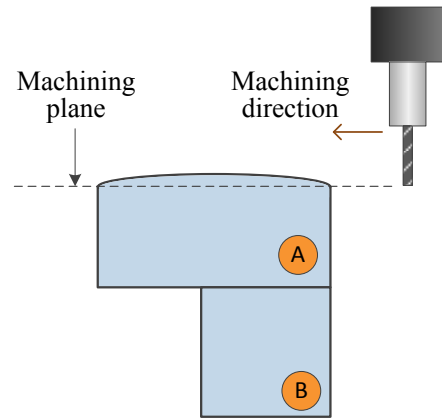
- If the feature is not accessible anymore, the last merged subpart that causes this tool inaccessibility issue will be re-decomposed into the original subparts. More merged subparts will be re-decomposed until there is at least one TAD that can be obtained.
- When sequencing an additive operation to fabricate the re-decomposed subparts, they should meet the deposition nozzle accessibility requirements.
- The subtractive operations for machining the exposed features are scheduled in the end of the process sequence because these features can always be machined.
- Subtractive operations will also be scheduled for removing the support material if needed.
- Finally, as mentioned in section 5.6.5, subtractive operations will be arranged in order to get a flat surface to be used as a build platform for the subsequent additive operations or a datum for the subsequent subtractive operations.

5.7. Feature modification for additive operations

Having obtained the operation sequences together with the build directions, the next step is to modify the dimensions of the features on the subparts. This is because, while new material is added onto the subpart that has been previously built or machined, non-uniform temperature gradients cause thermal stresses to build up, leading to distortion, dimensional deviation or even inner layer cracking [36]. As a new additive operation starts, bonding between the newly deposited layer and the previous layer takes place by local re-melting of previously solidified material and diffusion [37]. The heating and rapid cooling cycles of the material lead to non-uniform thermal gradients that cause continuous stress accumulation, resulting in further distortion between the existing part and the part built upon it. Therefore, the relevant features need to be modified for the subsequent additive and subtractive operations. For example, subpart B will be built onto subpart A, resulting in 2mm distortion on subpart A (see Fig. 11(a)). Thus, extra 2mm in thickness will be assigned to the bottom of subpart A before it is created, allowing the bottom face of subpart A to be finish machined in order to compensate the tolerance loss as a result of part geometric distortion, as illustrated in Fig. 11(b).



(a) add subpart B onto subpart A



(b) machine the warped bottom of subpart A

Fig. 11 Feature modification.

5.8. Post-processing stage

In this stage, the inspection operations will be added into the scheduled sequences of the additive and subtractive operations. Upon inserting inspection operations, the production times for these operation sequences will be estimated. By doing so, the most appropriate operation sequence is determined.

5.8.1. Integration of inspection operations

The inspection process should be used before the following operations take place:

- (i) Machining operations.

An inspection operation is scheduled before a machining operation starts, identifying the amount of material that should be removed from the deposited features. If the deposited feature is smaller than its nominal size, as identified in the inspection operation, further deposition operations will be added before the machining operation is executed.

- (ii) Additive operations for creating child parts.

Inspection operations are conducted before a child part is deposited onto an un-machined parent part due to the differing heights of the parent part that could result in the change of depositing parameters. As a parent part is built and has not been machined, its actual height is unknown. If the actual height is 10.2mm, a layer thickness of 0.2mm should be used in the following additive operation, depositing the child part from 10.4mm. If the actual height of the parent part is 10.25mm, a 0.25mm layer thickness is required, depositing material from 10.5mm. This is also concerned with bonding strength between two subparts.

- (iii) Additive operations that lead to the cutting tool inaccessibility.

In order to measure internal features, inspection has to be carried out when the features are still accessible. In this study, the touch trigger probe measuring method is used. The probe accessibility is the same as the cutting tool accessibility. Referring to the example shown in Fig. 8(d), the actual dimensions of the internal pocket on subpart 1 have to be measured before adding subpart 3. Similarly, the two highlighted pockets on subpart 2 have to be measured prior to producing subpart 4 and 5, respectively.

- (iv) The final inspection operation is scheduled at the end of the complete operation sequence, ensuring that the part dimensions are within the part tolerances.

5.8.2. Production time estimation and generation of static process plan

After obtaining all viable sequences, the production time for each independent sequence is calculated in order to decide the final operation sequence to implement. The total production time for manufacturing a part is defined as the sum of the time used in the additive, subtractive and inspection operations as well as switching time between additive, subtractive and inspection operations, as depicted in Equation 1.

Equation 1
$$T = T_a + T_s + T_c + T_m$$

where T is the overall production time, T_a is the time for the additive process, namely build time; T_s is the time used in the subtractive process; T_c is the switching time between the additive and subtractive operations, which includes machine set-up time; T_m is the inspection time.

Machining time estimation has been extensively researched and a method proposed by Heo *et al.* [38] is adopted in RP²A. Since the part is decomposed into a number of small subparts with fewer features, the inspection time can be simply considered as constant at this stage. By contrast, the additive operations consume considerably longer time than that of other operations. Therefore, a build time estimation model has been developed [39], which is depicted in Equation 2, where V is the part volume, H is the part height, ρ is the porosity and η is the intermittent factor which is defined for representing the ratio of nozzle deposition distance and repositioning distance.

Equation 2
$$T_a = 168.33 + 23.56V + 9.44H + 160.19V\rho + 78.17H\eta + \varepsilon$$

This equation can be used to estimate the build time directly from a CAD model and/or 2D drawings, which are the most accessible geometrical information for RP²A [39]. To this end, the most appropriate process sequence (i.e. the final process sequence) is where the least amount of production time is identified. The process parameters for the FFF process and CNC machining are selected, by

which the static process plan has been fully developed and it will be updated during production by adding new operations to the plan.

6. Generation of dynamic process plan

Due to the integration of inspection, the iAtractive process is able to react promptly to quality changes. Dynamic process plans are generated during the production of the part based on the knowledge of the static plan generation, according to the feedback of inspection information. Operations are adjusted and added into the static process plan if necessary. By doing so, quality changes can be identified in the early stage of production rather than in the final inspection.

Given that there is only one static process plan where a number of subparts together with the specific build directions and operation sequence are specified, it is inferred that the updated dynamic process plan will not disorganise the initial static process plan. The operation that leads to the dimensions of the subpart being out of tolerance is considered to be a failed operation. The subpart produced in the failed operation is called an unqualified subpart. The aim of generating dynamic process plans is to add extra operations to ensure that the dimensions of the subpart are in tolerance before continuously implementing the operations scheduled after the failed operation. This can be achieved by adding and/or removing material from the subpart. The amount of material to be deposited and/or removed depends on inspection feedback.

There are two methods that can be used to generate dynamic process plans. Fig. 12 illustrates the first method for generating a dynamic process plan, where each block represents one single operation. The symbol '+' denotes additive operation, '-' denotes subtractive operation and 'I' denotes inspection operation. The blue blocks are the operations that are sequenced in the static process plan; the grey blocks are the new operations added in the dynamic process plan; the arrows denote the operation sequence and the cross (×) denotes the cancelled static operation sequence. Every output of the inspection operations could be the start of the dynamic plan if the inspection results indicate that the subpart manufactured does not achieve the designed requirements in terms of dimensions and tolerance. New additive, subtractive and inspection operations will be added after the failed operation. The output of the dynamic process plan leads to the operation sequenced after the failed operation in the static process plan, as illustrated in Fig. 12. This is where the output of the first set of addition operations (in the yellow box) leads to the subtractive operation originally sequenced after the failed additive operation. The next start of the dynamic plan will be the next inspection operation that identifies the unqualified features.

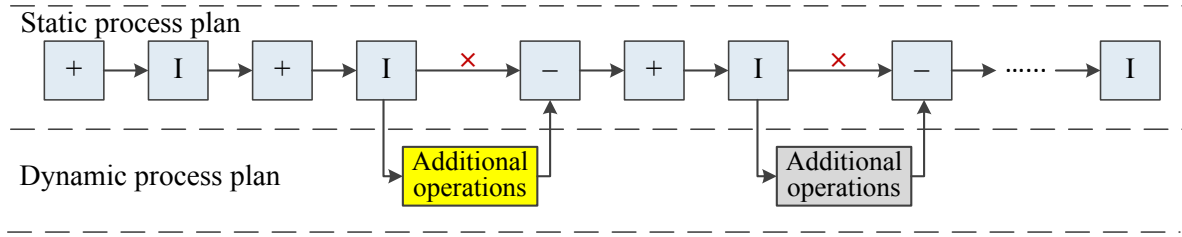


Fig. 12 The first method for generating dynamic process plans.

Another possible method for generating dynamic process plan is to:

- remove all the operations sequenced after the failed operation in the static process plan;
- run through the process planning stages presented in section 5.3 – 5.8;
- utilise the subparts that have already been produced and generate new operations to further manufacture the subparts until the final part is manufactured;
- if unqualified subparts are identified in the new operations, remove all the operations sequenced after the failed operation in the dynamic process plan, and repeat the above three steps.

This alternative method is illustrated in Fig. 13. The red arrows represent the actual operation sequences implemented; the black arrows represent the operations that were going to be conducted, but were abandoned in the production phase; the blue blocks are the operations in the static process plan; the grey blocks are the new operations scheduled in the dynamic process plan; and the purple blocks are the failed operations. Using the method shown in Fig. 12 or the method depicted in Fig. 13 depends on production times.

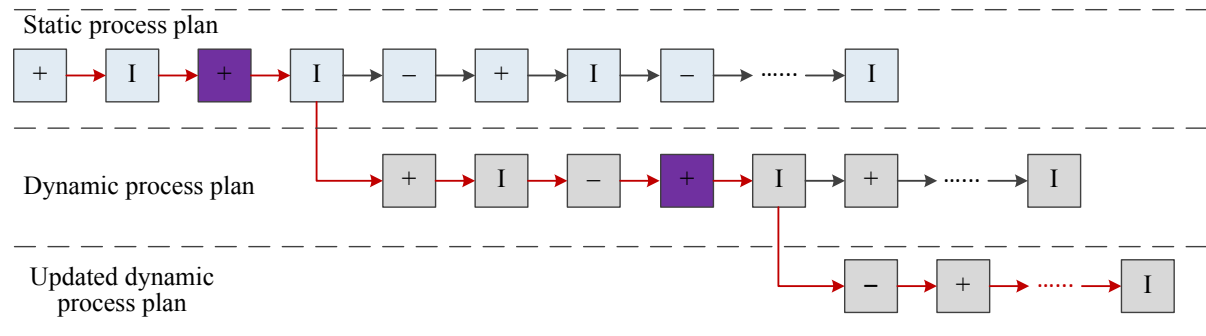


Fig. 13 An alternative method for dynamic process plan generation.

7. Case study

A case study was conducted to demonstrate the feasibility of the iAtractive process together with the developed reactionary process planning algorithm.

A block with four connected pockets and a hole is shown in Fig. 14(a). All the corners (except the corner where the hole is located) are round corners with 3mm radii, but for better representation they

are intentionally ignored in Fig. 14(b). All surfaces require finish machining. As a result, the part was decomposed into a number of subparts, which were then further merged into 5 subparts as shown in Fig. 14(c) and Fig. 14(d) (sectional view). The operation sequence in the static process plan is listed in Table 1. For the produced subparts, they are represented as ‘subpart $n\&(n+1)$ ’. The symbol ‘A’ represents the subpart that is additively built and has not been finish machined. For instance, subpart 2A is added onto subpart 1, and thus, the finished subpart is called subpart 1&2A. If subpart 1&2A has been finished machined, it is then called subpart 1&2.

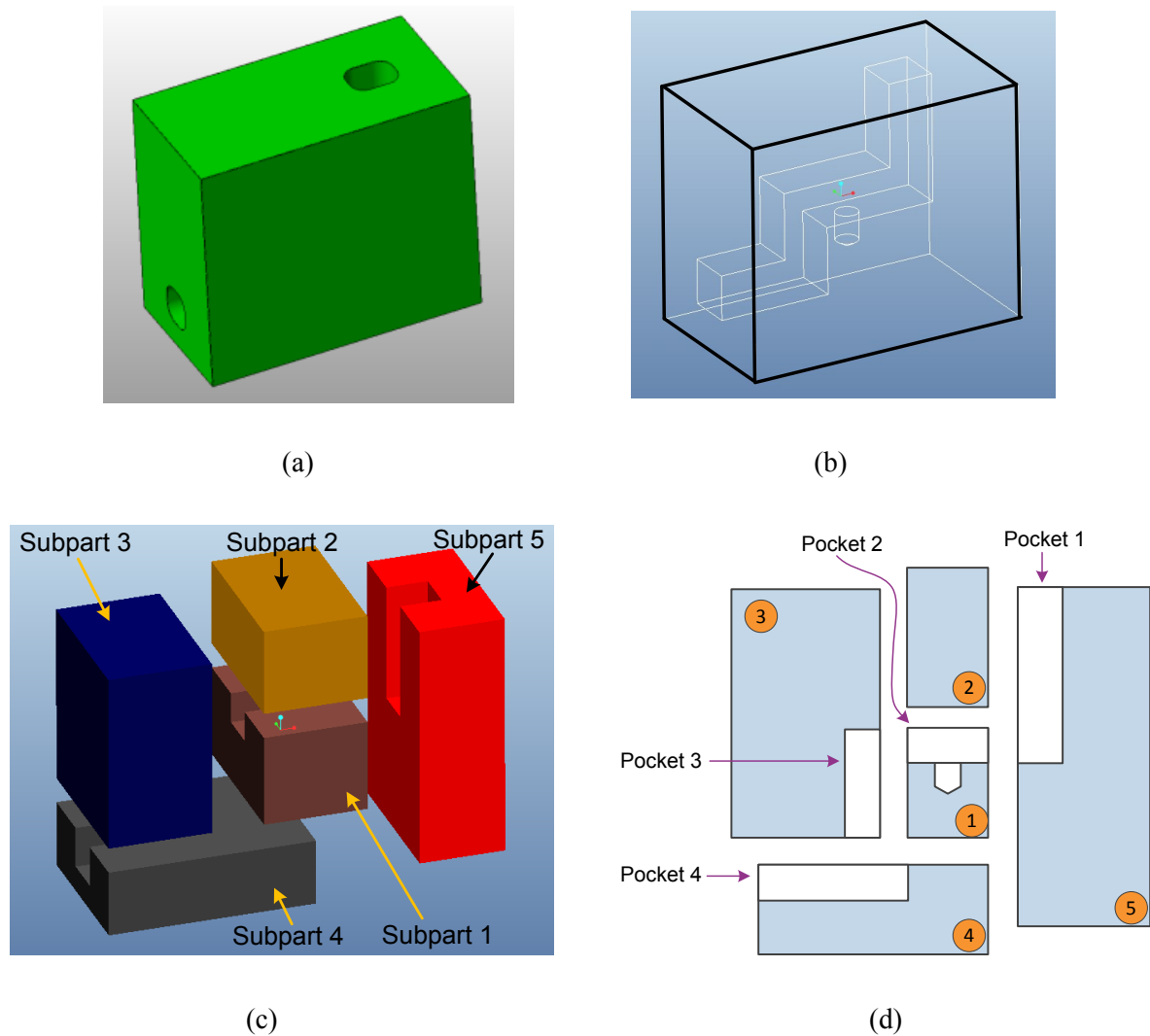


Fig. 14 The case study test part and the decomposed subparts.

Table 1

The developed static process plan for manufacturing the test part.

Operation sequence	Operation
1	Build subpart 1A by using the additive process

2	Measure the length, width and height of subpart 1A to obtain the dimensions of subpart 1A because subpart 1A is considered as raw material for the next operation
3	Machine pocket 2 on subpart 1A
4	Drill the hole on subpart 1A to obtain subpart 1
5	Measure the dimensions of the hole on subpart 1
6	Build subpart 2A onto subpart 1 to obtain subpart 1&2A
7	Measure the length, width and height of subpart 1&2A to determine the amount of material to be removed in the next operation (face milling)
8	Face mill the combined subpart 1&2A
9	Build subpart 3A onto the face milled subpart 1&2A to obtain subpart 1&2A&3A
10	Finish machine pocket 3 on subpart 3A (note: subpart 3A is already included in subpart 1&2A&3A). By doing so, subpart 1&2A&3 is produced
11	Measure the dimensions of pocket 3 as it will become inaccessible once subpart 4A is deposited onto subpart 1&2A&3
12	Build subpart 4A onto subpart 1&2A&3 to obtain subpart 1&2A&3&4A
13	Measure the length, width and height of subpart 1&2A&3&4A to determine the amount of material to be removed in the next operation (face milling)
14	Face mill the combined subpart 1&2A&3&4A
15	Finish machine pocket 2 on subpart 2A to obtain subpart 1&2&3&4A since machining pocket 2 will result in cutting tool inaccessibility issue if subpart 5A is produced
16	Measure the dimensions of pocket 2 on subpart 2 as it will become inaccessible after subpart 5A
17	Build subpart 5A onto subpart 1&2&3&4A to obtain subpart 1&2&3&4A&5A
18	Measure the length, width and height of subpart 1&2&3&4A&5A to determine the amount of material to be removed in the next operation
19	Finish machine pocket 1 on subpart 5A, including face milling of subpart 5A, to obtain subpart 1&2&3&4A&5
20	Finish machine pocket 4 on subpart 4A to finally obtain subpart 1&2&3&4&5, which is test part I
21	Measure the final part size and pocket 1 and 4

However, it was found that subpart 5 was out of tolerance in operation 18 (see Fig. 15(a)). As a result, three more operations were added into the process plan, namely, re-machine the side surface of subpart 5 (see Fig. 15(b)); then add material (green part, called subpart 6) onto it (see Fig. 15(c) and Fig. 15(d)); and finally finish machine it to the correct tolerance. The finished part is shown in Fig. 16(a). For showing the internal features, the part has been sectioned (40% material was removed), as shown in Fig. 16(b).

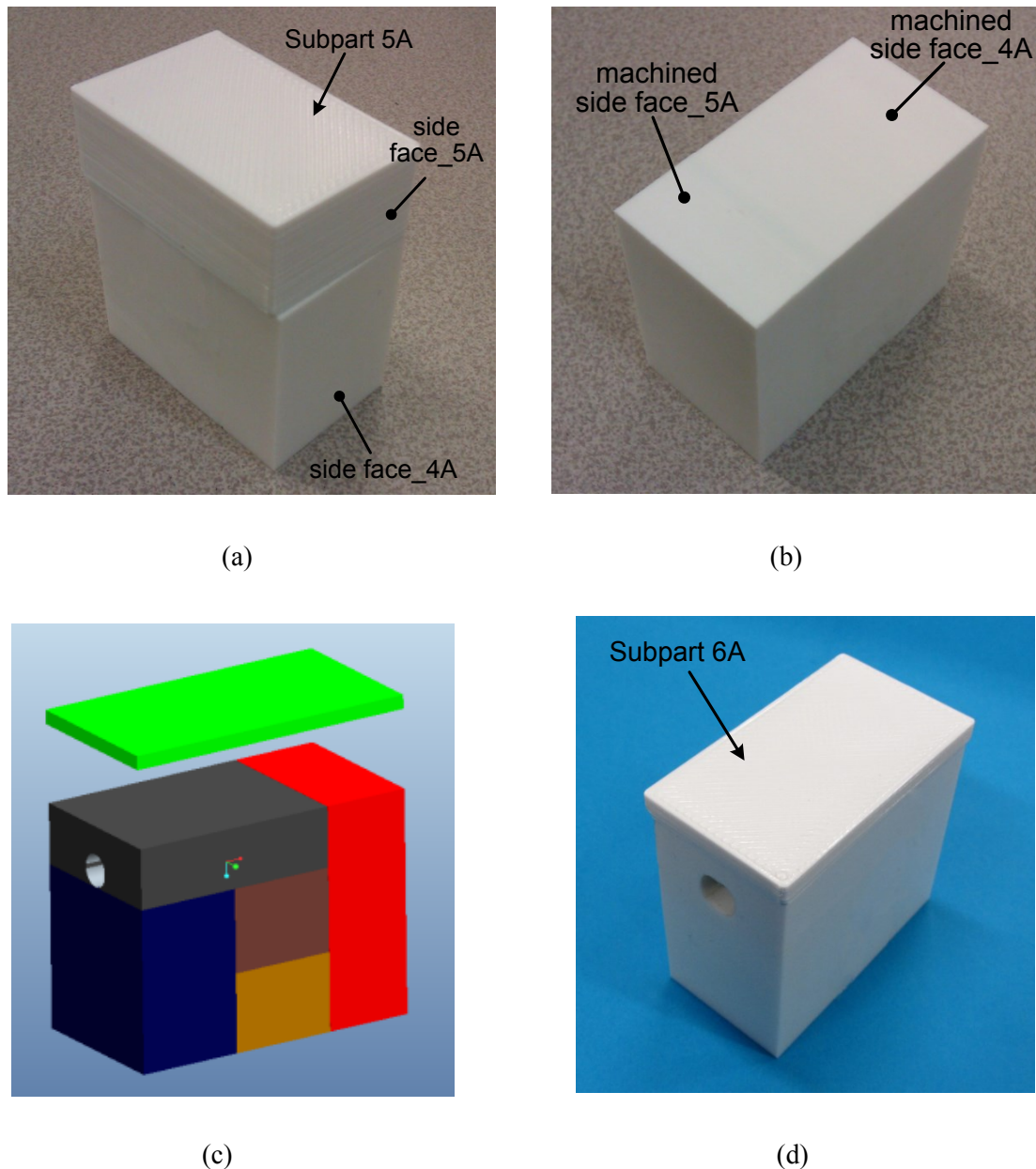
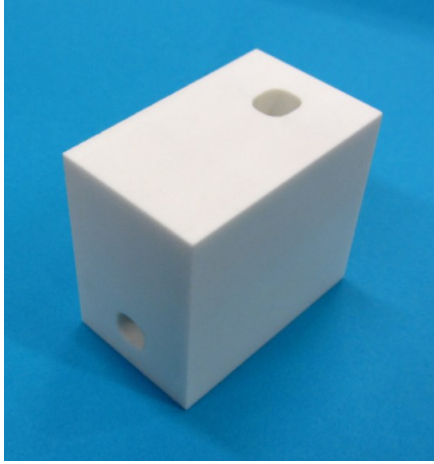
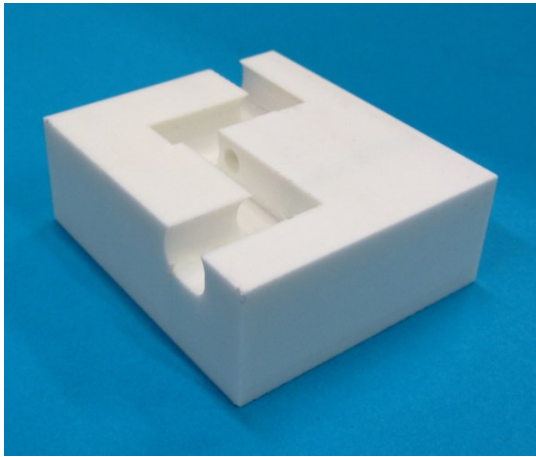


Fig. 15 The unqualified subpart 5 and adding subpart 6 in the dynamic process plan.



(a)



(b)

Fig. 16 The finished test part.

8. Discussion

In this paper, the iAtractive process consisting of additive, subtractive and inspection processes is proposed. RP²A generated process plans have been used to manufacture the test part depicted in Fig. 16 and demonstrate the feasibility of the iAtractive process. This algorithm acts as an enabler for flexibly and accurately manufacturing complex parts that are traditionally impossible to produce by either individual CNC machining or additive processes alone.

The major challenge in the development of RP²A was to establish a method to sequence additive, subtractive and inspection operations, whilst taking into consideration, the constraints of the individual processes and production times. The developed algorithm contains two major phases, namely, generation of static and dynamic process plans. A static process plan is first generated based on the given part design. The algorithm addresses the cutting tool accessibility, deposition nozzle

collisions and production times when generating operation sequences. The method that was proposed to organise operations, considers individual additive, subtractive and inspection operations in sequence. The additive operation sequences are first determined and then followed by inserting subtractive operations. The inspection operations are finally added into the correctly sequenced additive and subtractive operations.

By implementing the static process plan, the production time can be significantly reduced compared to the state of the art methods presented by Jeng and Lin [15] and Karunakaran *et al.* [5], since the redundant face milling operations for each layer have been removed. The manufactured parts can be achieved with a high level of accuracy and surface quality comparable to that of an entirely CNC machined part, whereas some of the features manufactured by adopting the Kerbrat *et al.* [27] approach could still remain inaccurate. The integration of inspection enables the iAtractive process to promptly respond to quality changes during production. Implementing the dynamic process plan, which is generated during production, enables the part to be manufactured appropriately, allowing the final product to be achieved with the correct tolerances.

9. Conclusions and future work

A number of inherent technical limitations of individual manufacturing processes have stimulated this research on hybrid manufacture. This paper introduced the novel hybrid process combining additive, subtractive and inspection processes in a serial manner. The reactionary process planning algorithm is developed, organising manufacturing operations and sequences, and determining appropriate parameters during production. It provides a novel intelligent solution to accurately manufacture complex parts (i.e. internal features), which are virtually impossible to produce using any existing independent manufacturing process.

Based on the given part design and available manufacturing resources, the part is orientated into an appropriate position and then decomposed into a number of subparts. The build direction of each subpart is specified, by which a number of sets of available build directions are obtained. The subtractive operations are inserted into the scheduled build direction allocation sequence by taking precedence and tool accessibility constraints into consideration. Finally, inspection operations are added into the sequences of the additive and subtractive operations when the features are still accessible by an inspection probe. After obtaining a number of feasible operation sequences, the best one in terms of production time is identified using the production time estimation model. As a result, a static process plan is first generated, which is ready for use but will be further updated according to the feedback of inspection operations during production. More operations will be added if the features are identified as being out of tolerance in the inspection operations. The case study demonstrated the efficacy of the developed process planning algorithm and indicates that the iAtractive process shows

significant superiority in terms of flexibility and capability as compared to individual additive and subtractive processes.

Future work will focus on developing and extending RP²A for manufacturing sculptured surfaces. The current RP²A still requires human intervention and thus a fully automatic RP²A system needs to be developed, realising automatic part production. The algorithm optimisation will be conducted to enhance the capability of RP²A, in particular in part decomposition and generation of dynamic process plans. Since the output of the part decomposition significantly determines the preceding steps in particular the operations to be used and the sequences to be scheduled, part decomposition methods require significant investigations. An ideal part decomposition approach needs to be capable of decomposing a complex part into a number of subparts whilst taking into consideration the capability of the individual processes. The optimal operation sequences can be realised by scheduling operations to manufacture these subparts. The iAtractive process will also benefit from the exploration of a robust strategy for generating dynamic process plans. This strategy needs to be capable of dealing with quality changes during production. According to the different quality changes, corresponding operations will be implemented to ensure the part being manufactured meets the designed requirements in the least amount of time.

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